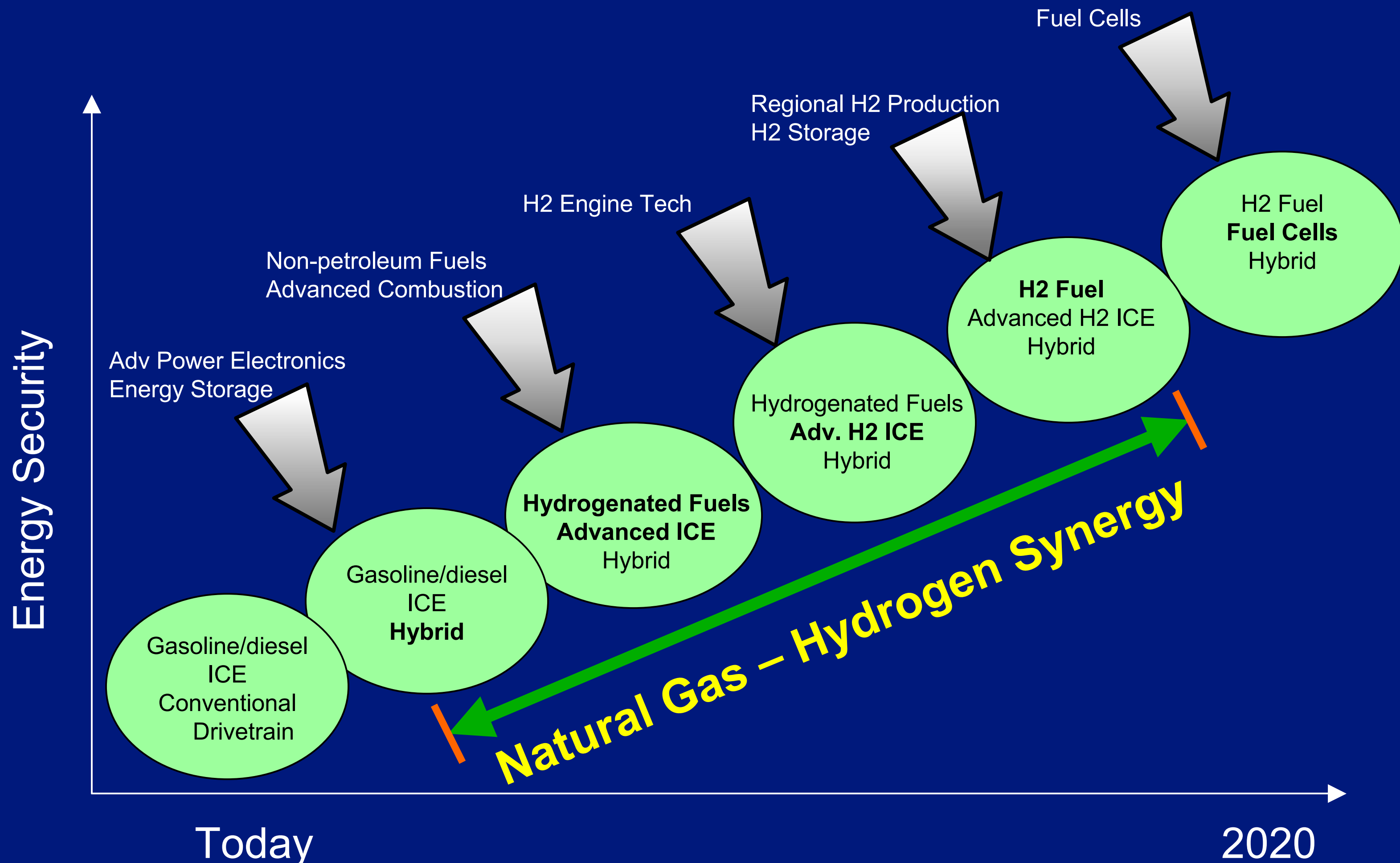
A Natural Transition

Leveraging DOE Natural Gas Vehicle Expertise to Aid the Transition to Hydrogen Vehicles of the Future

Dennis Smith, DOE Manager
Richard Parish, NREL, Team Leader
Mike Frailey, Margo Melendez, NREL
Denny Stephens, Kevin Chandler, Battelle
Doug Horne, Industry Consultant

FreedomCAR Pathway to Fuel Cell Vehicles and Hydrogen Economy



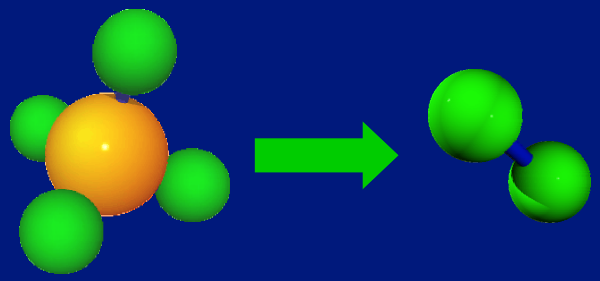
DOE NGV Expertise Can Facilitate Development of Hydrogen Vehicles

NGV development and deployment has occurred since enactment of the Alternative Motor Fuels Act of 1988

- This expertise has direct applicability to hydrogen vehicle and infrastructure development
- There are major synergistic benefits and leveraging opportunities through interaction of the NGV and Hydrogen fuel efforts
- Key elements of hydrogen vehicles and infrastructure can benefit from the foundation laid by NGVs

A Natural Transition to Hydrogen

DOE NGV expertise supports hydrogen vehicles



Natural Gas and Hydrogen: Gaseous fuels for vehicle applications

Commonalities

- √ Technical challenges
- √ Implementation challenges
- √ Funding sources & industry partners

Technical Challenges

DOE efforts to overcome NGV technical challenges now and in the past can benefit H_2 vehicle and infrastructure development

- Engine and Powertrain R&D
- Onboard Fuel Storage and Delivery
- Vehicle Integration
- Fueling Infrastructure
- Codes & Standards

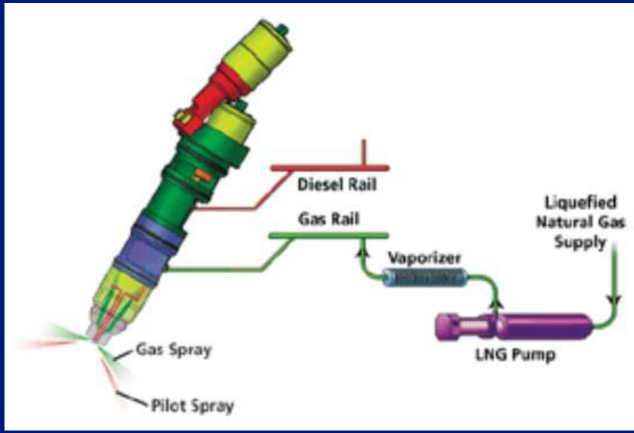
Technical Challenges

Engine and Powertrain R&D

Gaseous-fuel engine technologies developed for NGVs are applicable to HCNG and hydrogen ICEs

Gaseous-fuel engine technologies

- Spark-ignited natural gas, lean-burn
- Spark-ignited natural gas, stoichiometric
- High-pressure direct injection
- Micro-pilot
- Dual Fuel



Technical Challenges

Engine and Powertrain R&D

Gaseous-fuel engine technologies

	Description	Torque/HP	Emissions	Efficiency/ Economy
SING, lean-burn	~10:1 c/r, air throttle, TBI or PFI, turbocharged, lean-burn (up to 26:1), closed-loop	Commercially available Torque 375-1450 ft*lbs Horsepower 150-400 hp SING engines generate less HP and torque relative to DI diesels	Cummins, DDC, Deere, Mack certified to CARB Low NOx (2.0g) & 2004 EPA standard without a/t DDC S50G "Low NOx" project	Commercial products, ample in-use data 20-30% fuel economy penalty ~36% peak efficiency
Dual Fuel	~16:1 c/r, unthrottled, MPI (NG) DI (pilot), ~90% substitution, turbocharged, lean-burn (up to 34:1), closed-loop	Commercially available (Clean Air Partners) Torque 520-1250 ft*lbs Horsepower 190-410 hp	Certified to CARB Low NOx (2.5g) 2004 EPA capable NGNGV Phase I 0.5-g NOx w/EGR & CRT	Commercial products, limited in-use data ~20% fuel economy penalty ~38% peak efficiency
HPDI	~16:1 c/r, unthrottled, HPDI (pilot & NG), ~92% substitution, turbocharged, lean-burn (equivalent w/diesel ~100:1), closed-loop	Development engines in field (CWI) Torque 1450 ft*lbs Horsepower 400 hp "Low NOx" Development 1650 ft*lbs/450 hp	Certified to CARB Low NOx (2.5g) 2004 EPA capable CWI ISX-G "Low NOx" project	Preliminary in-use data 10-15% fuel economy penalty 42% peak efficiency "Low NOx" 41% peak efficiency

Technical Challenges

Engine and Powertrain R&D

Gaseous-fuel engine technologies

	Description	Torque/HP	Emissions	Efficiency/ Economy
Micro-Pilot (<1% pilot fuel)	~16:1 c/r, unthrottled, MPI (NG) DI (pilot), 99% or greater substitution, turbocharged, lean-burn, closed-loop	Prototype generator sets (Clean Air Partners) No automotive applications Torque and HP ratings equivalent to Dual Fuel, HPDI and diesel	Potential to meet 2010 EPA emission standards w/EGR & CRT	Same efficiency as Dual Fuel ~38% peak efficiency
SING, stoich w/EGR & TWC	Up to 12:1 c/r, air throttle, TBI or PFI (NG), turbocharged, stoichiometric a/f, EGR, TWC, closed-loop	Commercial stationary applications Phase II NGNGV Engine R&D projects Small rating increase relative to lean burn-SING	Potential to meet 2010 EPA emission standards	~40% peak efficiency

a/f—air fuel ratio; a/t—aftertreatment; CARB—California Air Resources Board; c/r—compression ratio; CRT—continuously regenerating technology; CWI—Cummins Westport Inc.; DDC—Detroit Diesel Corp.; DI—direct injection; EGR—exhaust gas recirculation; HCCI—homogeneous charge compression ignition; HPDI—high-pressure direct injection; MPI—multi-point injection; NG—natural gas; NGNGV—Next Generation Natural Gas Vehicle Activity; PFI—port fuel injection; SING—spark-ignited natural gas; stoich—stoichiometric; TBI—throttle body injection; TWC—three-way catalyst.

Technical Challenges

Engine and Powertrain R&D

Proven technology: gaseous-fueled engines commercialized and used in vehicles

<u>Engines Developed</u>

- Cummins 8.3G (275 hp)
- DDC S50G (300 hp)
- Deere 6081 (250 hp)
- Mack E7G (325 & 350 hp)
- DDC S60G (330 & 400 hp)
- Deere 6081 (280 hp)
- Cummins 8.3G Plus (280 hp)

<u>Ongoing NG engine development</u>

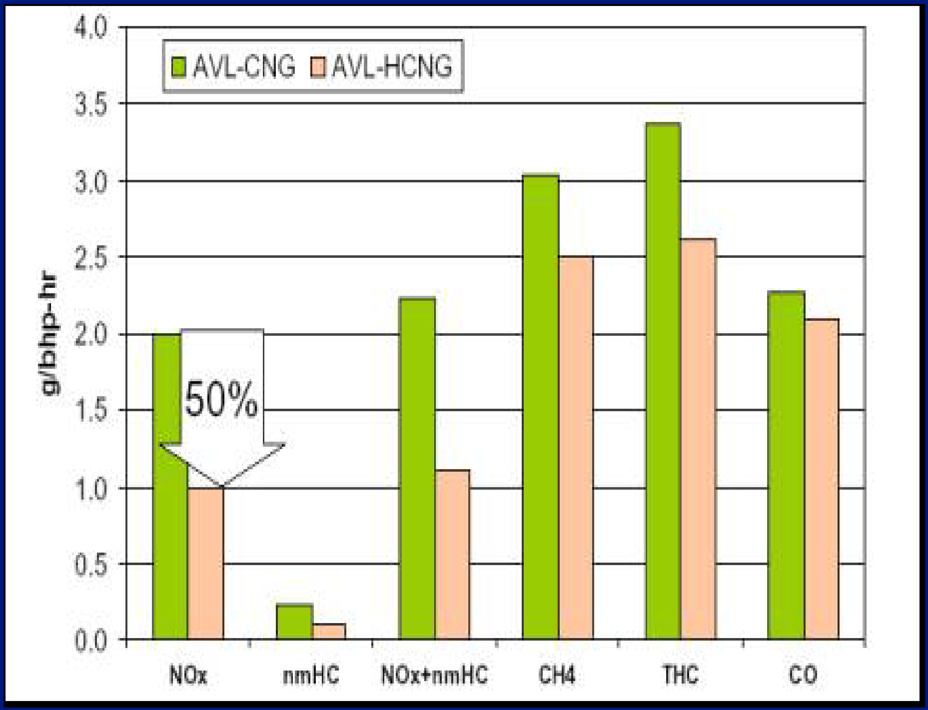
- Cummins Westport 8.9L (320 hp)
- Mack 11.0L (325 hp)
- Deere 8.1L (280 hp)

Technical Challenges

Engine and Powertrain R&D

Developing ICEs to use HCNG provides early fleet experience with hydrogen

- Ongoing HCNG project with Cummins-Westport and Sunline Transit Agency
- HCNG blend reduced NO_x emissions by 50% with no significant change in fuel efficiency while maintaining transient speed and torque capability
- Utilized 20% mole fraction of hydrogen in CNG

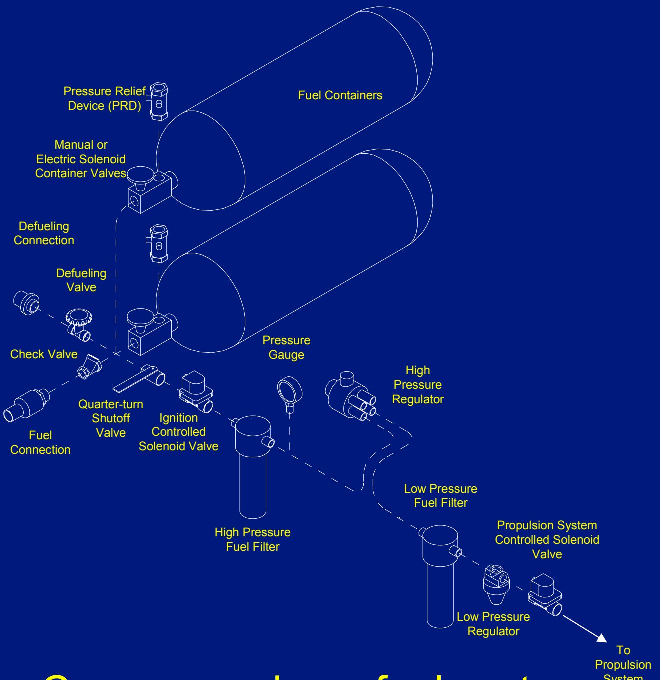


Technical Challenges

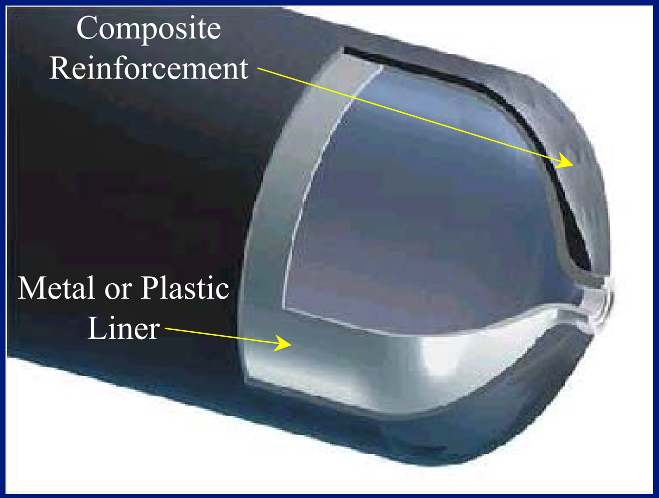
Onboard Fuel Storage and Delivery

Hydrogen fuel tanks and systems available today are evolutions of CNG and LNG tanks and systems

DOE has extensive experience improving safety and integrity of these fuel tanks and systems, including improved durability and crashworthiness.



Compressed gas fuel system

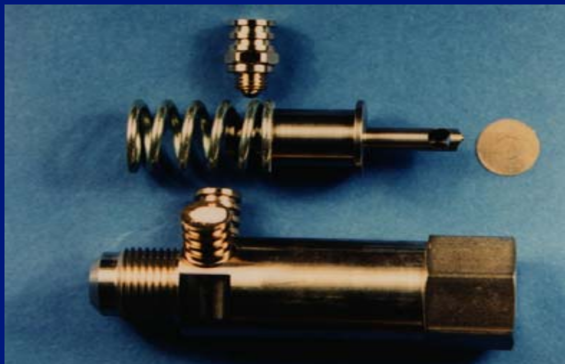


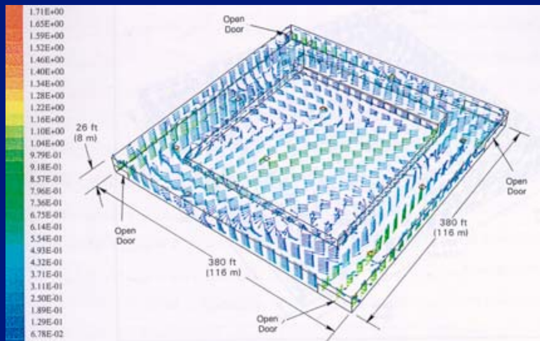
Composite fuel container

Technical Challenges

Onboard Fuel Storage and Delivery

Venting from high-pressure relief devices is critical for hydrogen and natural gas fuel tank and vehicle safety





Gaseous fuel cylinders must have high-flow pressure relief devices (PRDs) to vent gas and prevent rupture in case of fire

<u>Challenges successfully addressed</u>:

- Unintended venting from damaged PRDs
- Failure analysis of PRDs
- Improved PRD testing & standards to minimize unintended venting
- Improved vent piping design to avoid PRD damage
- CFD building ventilation design to evacuate vented fuel

Technical Challenges

Onboard Fuel Storage and Delivery

Reliable detection of an odorless, invisible gas is a critical safety element

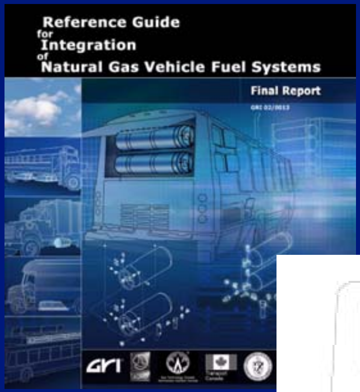
- Gas leak detection on the vehicle, at fueling station, and inside maintenance facilities is required
- Proper fail-safe gas detection and ventilation systems are necessary
- Electronic detection vs. odorant addition is still being debated for LNG

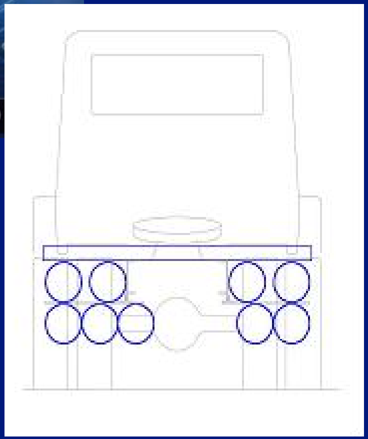
Technical Challenges

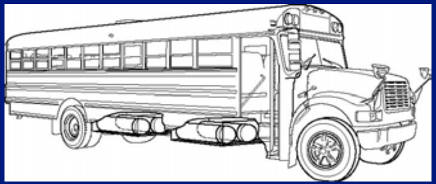
Vehicle Integration

Reliability and safety of gaseous fuel systems are critical to their acceptance by regulators, fleets, and the public

- Numerous medium- and heavy-duty vehicles have been integrated with natural gas systems under DOE programs
- Issues:
  - Packaging
  - Range
  - System venting
  - Safe operating procedures
  - Vehicle system warranties
- Developed a vehicle integration guide to improve reliability and safety of gaseous fuel systems







Technical Challenges

Fueling Infrastructure

Hydrogen infrastructure is building upon the technology developed for natural gas and faces similar obstacles

- Safety for public use
- Fuel quality
- Weights and Measures approved metering (GGE)
- Acceptance by local Fire Marshals, code officials, and the general public
- Standardization of fuel connectors
- Durability of high pressure fuel hoses and other components
- Cost efficiency, reliability, and maintainability
- Best practices for design and implementation of fueling equipment and maintenance facilities

Technical Challenges

Fueling Infrastructure

Home fueling will enhance consumer acceptance of gaseous fuels

Fuelmaker's "Phill" home refueling appliance

DOE is evaluating safety issues for a natural gas home fueling appliance, which can be the precursor for a hydrogen home fueling appliance

Technical Challenges

Codes & Standards

Most hydrogen vehicle codes and standards are based on those developed for NGV technology

- Current NGV codes & standards revisions are focused on knowledge resulting from advancing technology and practical experience
- Application to hydrogen can be addressed at the same time
  - Adjustments made for different physical/chemical properties and operating pressures
- Knowledge of NGV codes & standards processes can help navigation through hydrogen codes & standards processes

A Natural Transition to Hydrogen

DOE NGV expertise supports hydrogen vehicles

Natural Gas and Hydrogen: Gaseous fuels for vehicle applications

Commonalities

√ Technical challenges

√ Implementation challenges

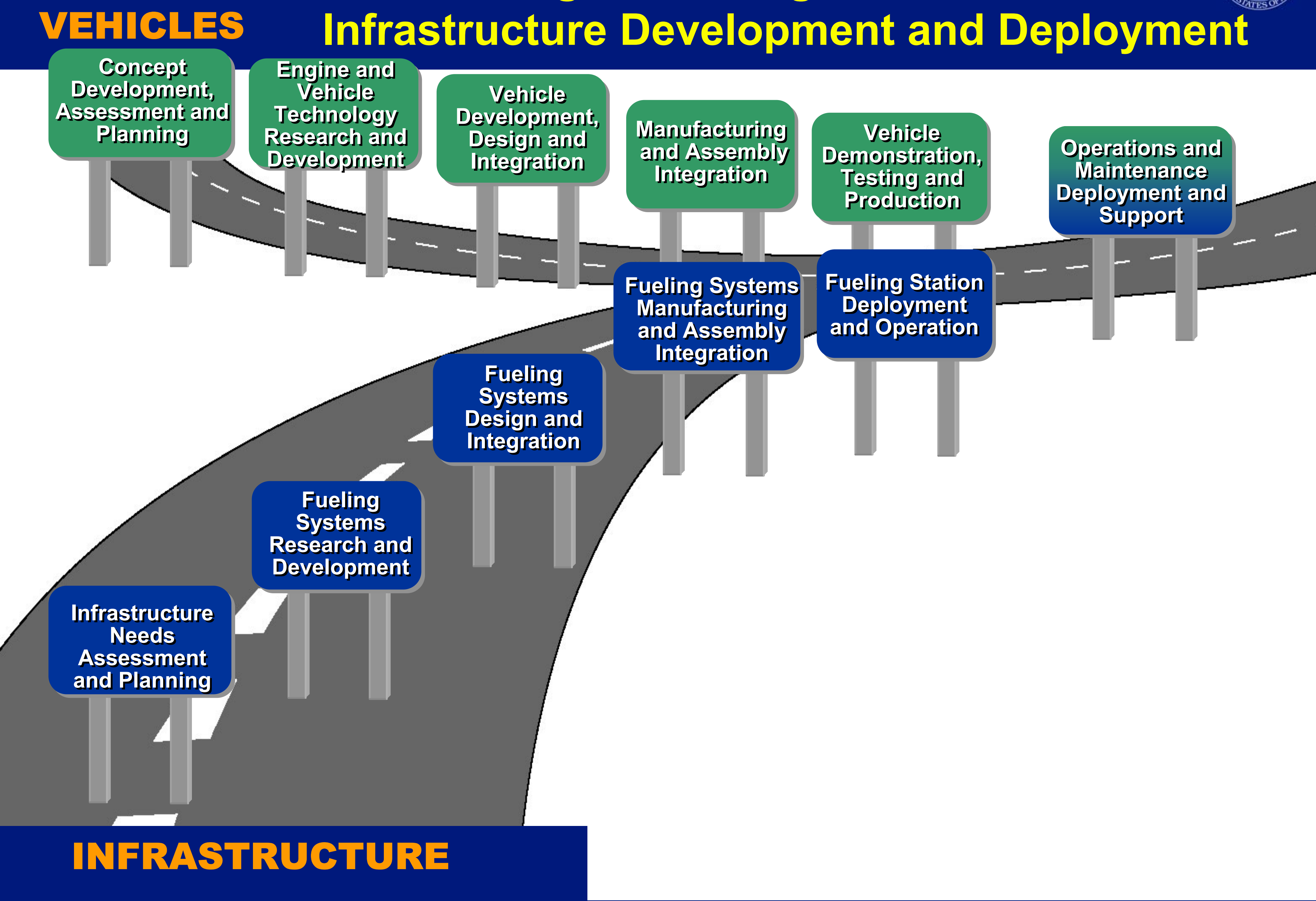
√ Funding sources & industry partners

Implementation Challenges

DOE efforts to overcome NGV implementation challenges apply directly to overcoming hydrogen implementation challenges

- Strategic Planning for Vehicle and Infrastructure Development and Deployment
- Vehicle Evaluation Programs
- Technical Assistance and Troubleshooting
- Consumer Awareness and Perceptions

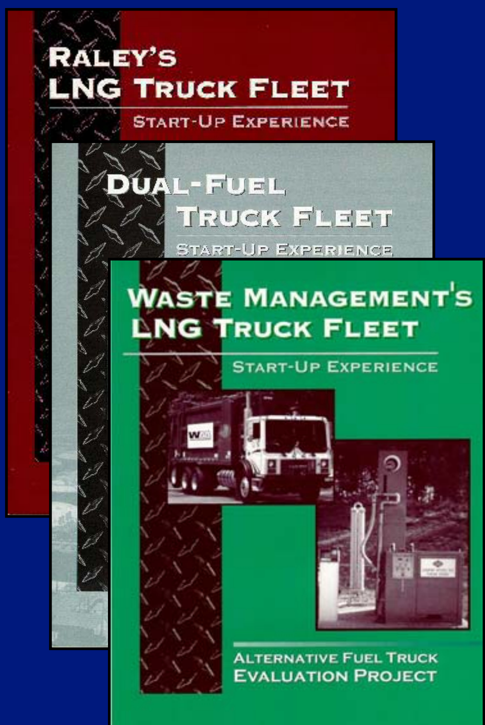
Strategic Planning for Vehicle and Infrastructure Development and Deployment



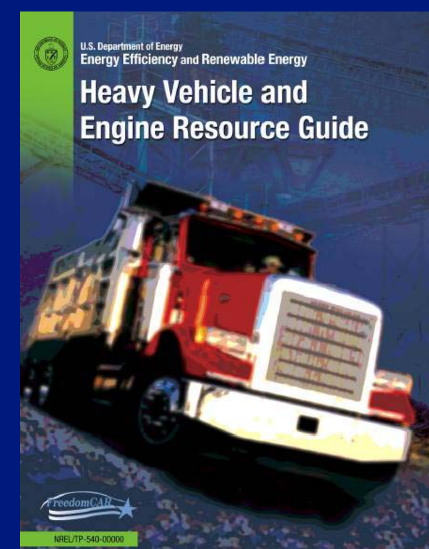
Implementation Challenges

Vehicle Evaluation Programs

Reliable and informed decision making is critical to the successful implementation of alternative fuels



- DOE collects, analyzes, and disseminates data on performance, reliability, costs, and emissions of alternative fuel vehicles
- Evaluations support successful introduction of new technology, assist fleets with implementation issues, document experiences for future reference, and give wide access to project results



Implementation Challenges

Technical Assistance & Troubleshooting

Troubleshooting and quick response to problems are critical to smooth implementation of alternative fuels

- Low-volume alternative fuel suppliers do not have the resources to address challenging problems
- NREL “Tiger Team” subcontractors provide technical support to stakeholders and rapid assistance with alternative fuel implementation
  - Station design and operation
  - CNG transit bus implementation
  - AFVs at airports
  - State AFV legislation analysis
  - Training and workshops

A Natural Transition to Hydrogen

DOE NGV expertise supports hydrogen vehicles

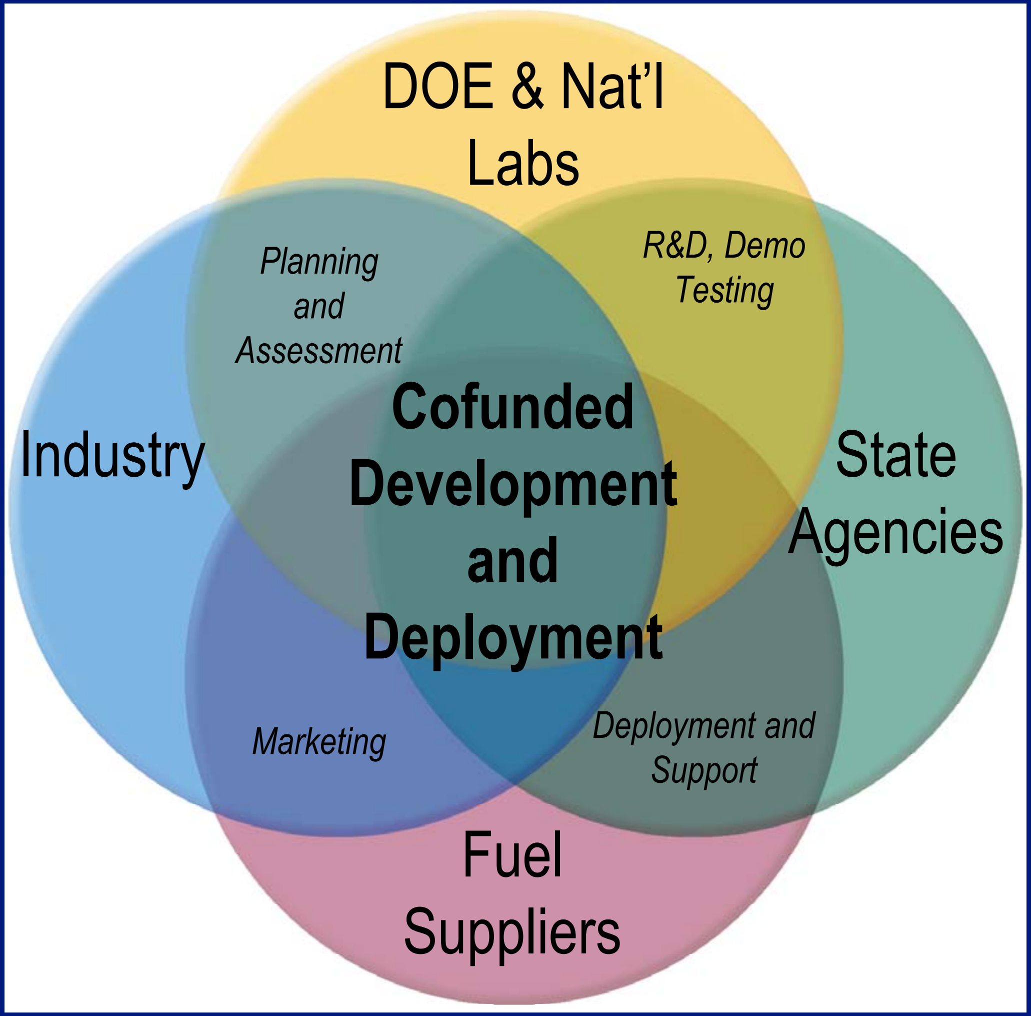
Natural Gas and Hydrogen: Gaseous fuels for vehicle applications

Commonalities

- √ Technical challenges
- √ Implementation challenges
- √ Funding sources & industry partners

Funding Sources & Industry Partners

Hydrogen vehicles are supported by many of the same OEMs, suppliers, and funding agencies in DOE's existing NGV network



Funding Sources & Industry Partners

Natural Gas Vehicle Technology Forum

NGV forum brings together important stakeholders, many of whom may play a key role with hydrogen vehicles

- Engine and vehicle manufacturers
- Fuel suppliers, retailers
- Funding agencies (DOE, SCAQMD, CEC)
- Technical experts
- Fleet managers

Funding Sources & Industry Partners

Hydrogen and Fuel Cell Partners

Hydrogen and fuel cell partnerships jump start hydrogen vehicle technology development

DOE involvement includes

- California Fuel Cell Partnership
  - Bus Team (vehicle evaluations)
  - VeOps Team (fleet & vehicle databases)
- Hydrogen bus evaluation activities
  - AC Transit fuel cell buses
  - SunLine Transit
    - HCNG
    - Fuel cell buses
  - Santa Clara Valley Transit fuel cell buses
  - European fuel cell bus

Funding Sources & Industry Partners

DOE-NREL/AVL Cooperative Research & Development Agreement

AVL is a world-class powertrain developer

- AVL has completed OEM-sponsored work with hydrogen ICEs
- $7.2M CRADA with $5.7M AVL contribution
- CRADA includes
  - Fuel cell modeling and validation
  - Vehicle thermal management systems modeling and development
  - Advanced combustion development and emissions modeling

NGV Lessons Learned

Lessons learned by DOE and industry through NGV work will pave the way for hydrogen vehicles

- Early NGV research emphasized engines and fuel tanks, expecting that industry would take care of the rest
- Stakeholders learned quickly that getting the details right is critical (e.g., refueling connectors, PRDs, fueling station reliability)
- Effective transitioning will require DOE support for the entire engine, vehicle, and infrastructure research, development, and deployment process

A Natural Transition to Hydrogen
Summary

- The DOE NGV Team is resolving challenges that overlap those facing implementation of hydrogen vehicles
  - √ Technical challenges
  - √ Implementation challenges
  - √ Funding sources & industry partners
- There are major synergistic benefits and leveraging opportunities through interaction of the FreedomCAR NGV and Hydrogen activities

A Natural Transition to Hydrogen

Recommendations

- Develop technical expert contact crosswalk list
- Re-examine/expand internal peer review practices
- Consider joint project development for common efforts
- Consider integrating stakeholder coordination efforts